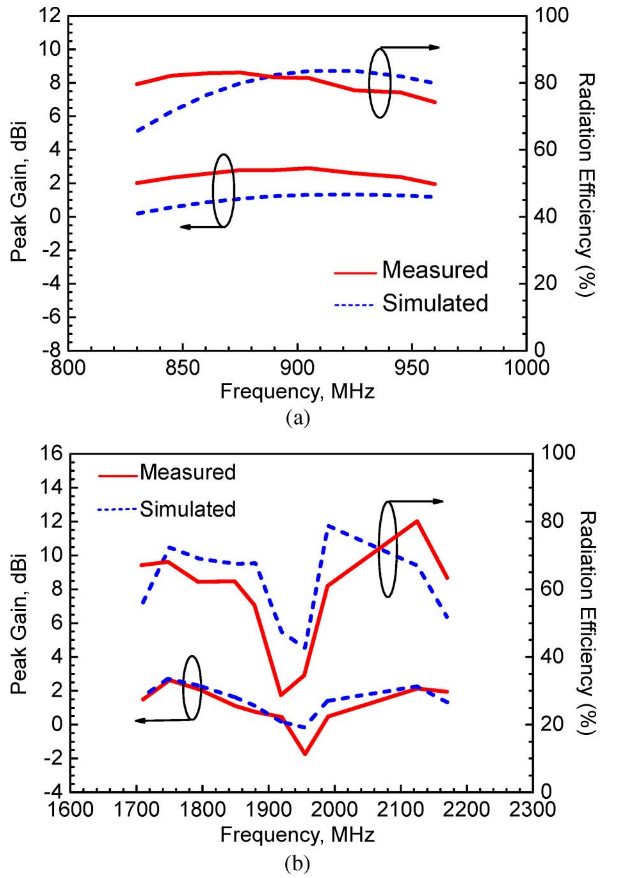

Fig. 9. Measured and simulated antenna gain and radiation efficiency of the proposed antenna. (a) The lower band for GSM operation. (b) The upper band for DCS/PCS/UMTS operation.

slots. The different coupling effects of the slotted structure make it controllable for the excitation of a quarter-wavelength resonant modes at about 1795, 1920, and 2045 MHz, respectively. The two excited resonant bands cover GSM and DCS/PCS/UMTS operations for the proposed antenna in this study.

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Printed Single-Strip Monopole Using a Chip Inductor for Penta-Band WWAN Operation in the Mobile Phone

Kin-Lu Wong and Shu-Chuan Chen

***Abstract*—A single-strip monopole capable of generating two wide operating bands at about 900 and 1900 MHz covering GSM850/900/1800/1900/UMTS penta-band WWAN operation in the mobile phone is presented. The monopole has a simple structure of an inverted-L shape to be printed on the no-ground region of the system circuit board of the mobile phone. By simply embedding a chip inductor at the proper position in the strip monopole, the first two resonant modes of the monopole can have a frequency ratio of about 1 to 2 (instead of 1 to 3 for the traditional monopole) to respectively cover the desired wide 900 and 1900 MHz bands. In addition, the total strip length can be less than the required 0.25 wavelength (about 0.17 wavelength in this design) for the fundamental resonant mode excitation of the proposed monopole; this behavior is owing to the embedded chip inductor compensating for the increased capacitance seen at the feeding point with the decreasing strip's resonant length. The SAR of the proposed monopole placed at the bottom position of the mobile phone is found to meet the SAR limit for practical applications.**

***Index Terms*—Handset antennas, internal mobile phone antennas, mobile antennas, multiband antennas, WWAN antennas.**

I. INTRODUCTION

It has been known that, by embedding a chip inductor, the monopole can have decreased resonant length for achieving its fundamental or lowest resonant mode excitation [1]–[3]. This behavior is owing to the additional inductance contributed by the embedded chip inductor to compensate for the increased capacitance resulting from the decreased resonant length of the antenna. Related works on the shortened dipole and monopole with this kind of inductive loading have also been available in the open literature. They include the shortened dipole with the inductive element placed in series with each radiating arm of the dipole [4] and the multi-branch monopole with one of its branches end-loaded with a dense meandered section as the inductive end section [5]. It has also been shown that the chip inductor should be embedded near the feeding point of the monopole [1] where the excited surface currents are strong for the fundamental resonant mode. In this case, the required resonant length is usually less than 0.2 wavelength for generating the fundamental resonant mode of the monopole. Also, it is found that the required resonant length of the second resonant mode of the monopole will be decreased as well such that the frequency ratio of the first two resonant modes maintains about 1 to 3, similar to that of the traditional monopole or dipole [6]–[8]. Hence, in order to obtain two wide bands at about 900 and 1900 MHz to cover GSM850/900/1800/1900/UMTS wireless wide area network (WWAN) operation, two separate radiating strips are usually required for the internal WWAN antenna for mobile phone applications [1], [9].

In this communication, we propose a printed single-strip monopole using a chip inductor for penta-band WWAN operation in the mobile phone. The embedded chip inductor can result in a decreased resonant length for the fundamental resonant mode excitation of the monopole. It can also generate an additional resonant mode such that the first two

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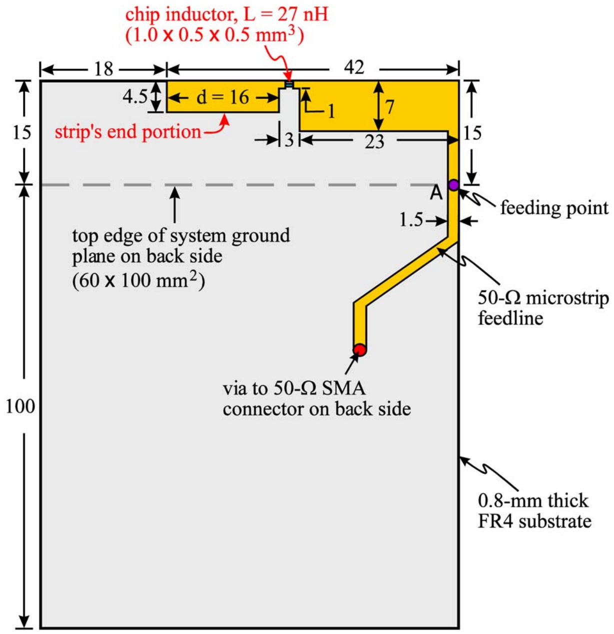


Fig. 1. Geometry of the proposed single-strip monopole antenna embedded with a chip inductor for penta-band WWAN operation in the mobile phone.

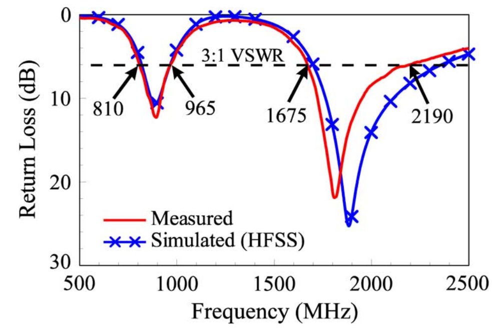


Fig. 2. Measured and simulated (HFSS) return loss for the proposed antenna.

resonant modes of the monopole can be adjusted to have a frequency ratio of about 1 to 2 to respectively cover the desired wide 900 and 1900 MHz bands for GSM850/900 (824–894/880–960 MHz) and GSM1800/1900/UMTS (1710–1880/ 1850–1990/1920–2170 MHz) operation. This behavior of dual-band operation is similar to that of using an LC resonator applied to a PIFA [10] and that of using an inductive element loaded in each radiating arm of a dipole [4]. In this study, the use of a chip inductor applied to a single-strip monopole leads to a simple uniplanar structure with a small planar printed area (about 250 mm^2 here) in the mobile phone. The printed area is much smaller than that of the traditional two-strip monopoles for penta-band WWAN operation in the mobile phone that have been reported (about 350 mm^2 in [1] and 420 mm^2 in [9]). In addition, the uniplanar structure of the antenna is very promising for thin-profile or slim mobile phone applications [11]–[17], which is becoming attractive for the mobile users. Also, when arranging the antenna to be at the bottom position of the mobile phone, the simulated SAR (specific absorption rate) [18]–[22] is found to meet the limit of 1.6 W/kg for 1-g head tissue and 2.0 W/kg for 10-g head tissue.

II. Proposed Antenna

Fig. 1 shows the geometry of the proposed antenna, which is mainly an inverted-L strip monopole embedded with a chip inductor of $L = 27\ \mathrm{nH}$. The chip inductor of $0.5 \times 0.5 \times 1.0\ \mathrm{mm}^3$ separates the strip into two sections: a front section and an end section. The two sections are printed on the no-ground portion ($15 \times 60\ \mathrm{mm}^2$) of the system circuit board, which uses a 0.8-mm thick FR4 substrate of $115 \times 60\ \mathrm{mm}^2$ in this study. On the back side of the circuit board, a system ground plane of $100 \times 60\ \mathrm{mm}^2$ is printed. The dimensions of the system circuit board and ground plane are reasonable for practical mobile phones, especially for smartphones.

The total length of the antenna from the feeding point A, through the chip inductor, to the open end has a length of about 57 mm only (about 0.17 wavelength at 900 MHz). Although the strip length is less than 0.25 wavelength at 900 MHz, a wideband resonant mode covering the GSM850/900 bands can be generated. This behavior is owing to the additional inductance contributed by the chip inductor to compensate for the increased capacitance with decreased resonant strip length.

On the other hand, at higher frequencies around 1900 MHz, the chip inductor provides a large inductive reactance such that the front section of length about 38 mm (about 0.24 wavelength at 1900 MHz) sees a virtual open circuit at the chip-inductor position. This condition leads to the excitation of a new quarter-wavelength mode at about 1900 MHz, which shows a wide bandwidth to cover GSM1800/1900/UMTS bands. Note that the wide bandwidths of the first two resonant modes of the antenna at about 900 and 1900 MHz are mainly resulted from the selection of widened widths (7.0 and 4.5 mm here) of the front and end sections. It has been shown that by increasing the width of the strip monopole, the antenna's impedance matching can be improved, and hence the obtained bandwidth can be widened [23].

Note that the antenna occupies a printed area of about 250 mm^2 only. Owing to the small printed area, there is a large portion unused and available in the no-ground portion of the circuit board for accommodating the associated elements such as the speaker [24], [25], the lens of the digital camera [26], and so on. For testing the antenna in the experiment, a 50-Ω microstrip feedline printed on the front side of the circuit board and connected through a via-hole to a 50-Ω SMA connector on the back side of the circuit board is used. The obtained results are presented in Section III.

III. Results and Discussion

Fig. 2 shows the measured and simulated return loss for the proposed antenna. Good agreement between the measured data and the simulated results obtained from Ansoft HFSS [27] is obtained. Two wideband resonant modes at about 900 and 1900 MHz are obtained. The first and second modes provide wide bandwidths of 155 MHz (810–965 MHz) and 515 MHz (1675–2190 MHz) to cover the GSM850/900 and GSM1800/1900/UMTS bands, respectively, for WWAN operation.

Fig. 3 shows the simulated return loss for the proposed antenna, the case without the chip inductor (Ref 1), and the case with a chip inductor of 10 nH placed near the feeding point (Ref 2). Ref 1 can be considered as a simple monopole using a connecting strip of $1.0 \times 1.0\ \mathrm{mm}^2$ to replace the chip inductor in the proposed antenna. It is seen that the lowest mode of Ref 1 occurs at about 1100 MHz, higher than those of the proposed antenna and Ref 2. In addition, the second mode of Ref 1 occurs at about 3300 MHz; that is, the first two modes have a frequency ratio of about 1 to 3. For Ref 2, with the chip inductor having a smaller inductance of $L = 10\ \mathrm{nH}$ than that in the proposed antenna, the lowest mode can also occur at about 900 MHz, similar to the proposed antenna. Note that when the chip inductance has an inductance of 27 nH, the same as that in the proposed antenna, the lowest mode can be shifted to lower frequencies at about 700 MHz. Also, the second mode of Ref 2 occurs at about 2800 MHz, about three times that of the lowest mode. That is, both the first two modes of Ref 1 and Ref 2 have

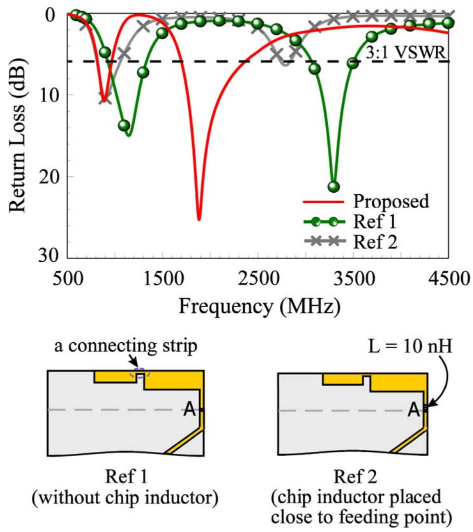


Fig. 3. Comparison of the simulated (HFSS) return loss for the proposed antenna, the case without the chip inductor (Ref 1), and the case with a chip inductor of 10 nH placed near the feeding point (Ref 2).

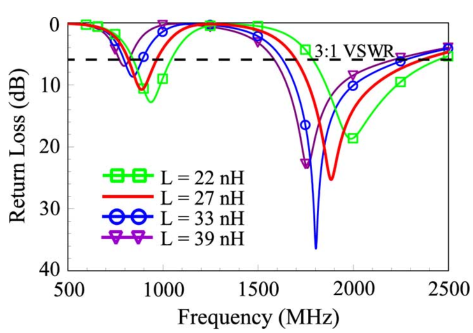


Fig. 4. Simulated (HFSS) return loss of the proposed antenna as a function of the inductance L of the chip inductor.

a frequency ratio of about 1 to 3, similar to the traditional monopole. Hence, an additional strip is required to generate a resonant mode at about 1900 MHz to cover the GSM1800/1900/UMTS bands. A longer strip is also required for Ref 1 to generate a resonant mode for operating in the 900 MHz band.

Fig. 4 shows the simulated return loss as a function of the inductance L of the chip inductor. The increasing inductance causes the lowering of both the first two modes, and a frequency ratio of about 1 to 2 is maintained. It is noted that when a larger inductance is used, the obtained bandwidth of the lowest mode is decreased with the decreasing of its resonant frequency. Fig. 5 shows the simulated return loss as a function of the end-portion length d. In this case, when the length d varies, the total length of the antenna also varies. It is seen that, with the front-section length fixed as 23 mm, the second mode at about 1900 MHz is very slightly affected for various lengths of d from 10 to 20 mm. On the other hand, the lowest mode is shifted to lower frequencies when the length d increases. However, the impedance matching is also degraded when the lowest mode is shifted to lower frequencies. The results obtained in Figs. 4 and 5 indicate that the desired lower and upper modes of the antenna can be effectively controlled by adjusting the inductance L of the chip inductor and the length d of the end section.

The radiation patterns of the proposed antenna are studied, and good agreement between the measured and simulated patterns is obtained. Dipole-like pattern is seen at 925 MHz for the 900 MHz band, while more directivity is obtained for the pattern at 1920 MHz

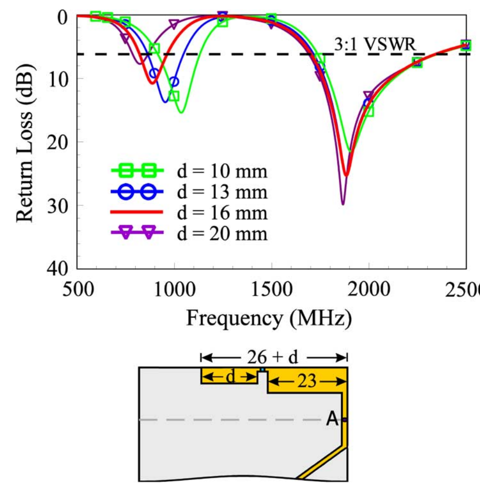
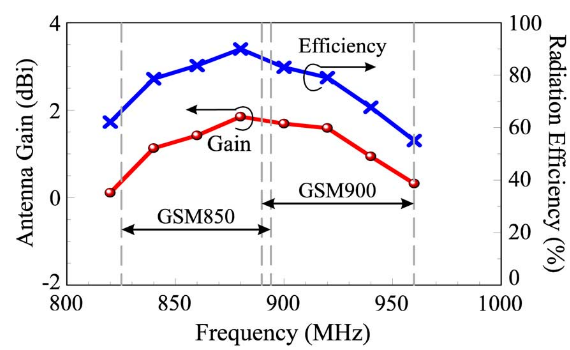
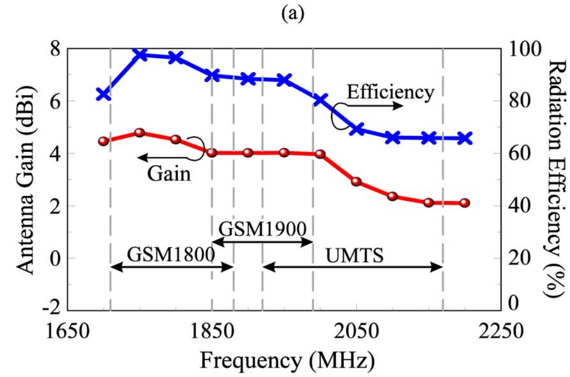


Fig. 5. Simulated (HFSS) return loss of the proposed antenna as a function of the end-portion length d.



(a)



(b)

Fig. 6. Measured radiation efficiency and antenna gain for the proposed antenna. (a) GSM850/900 bands. (b) GSM1800/1900/UMTS bands.

for the 1900 MHz band. The obtained radiation patterns including the polarization information are similar to those of the two-strip monopole obtained in [1] and those of the conventional internal mobile phone antennas [28].

The measured radiation efficiency and antenna gain are shown in Fig. 6. The radiation efficiency varies from 55 to 88% for the GSM850/900 bands [see Fig. 7(a)] and from 65 to 96% for the GSM1800/1900/UMTS bands [see Fig. 7(b)]. The antenna gain is 0.4–1.8 dBi and 2.07–4.8 dBi for the GSM850/900 and GSM1800/1900/UMTS bands, respectively. The obtained radiation characteristics with efficiency better than 55% are sufficient (generally required to be larger than 50% over the bands) for practical mobile phone applications.

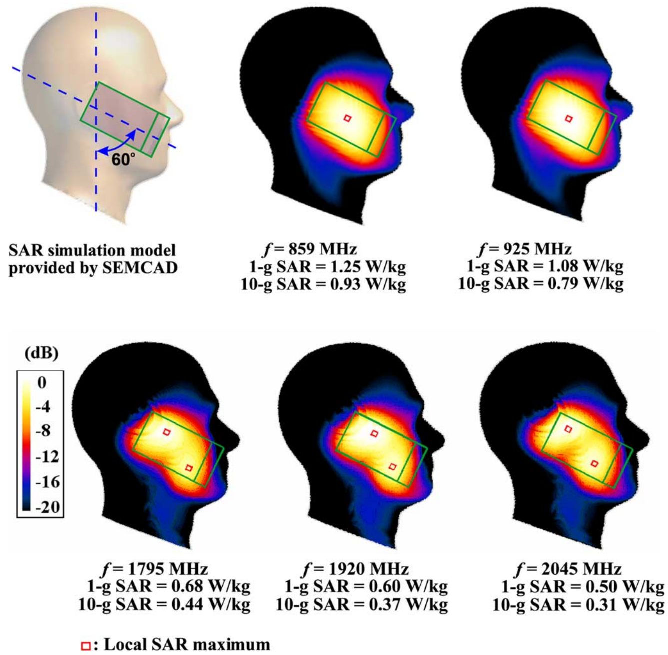


Fig. 7. SAR simulation model (SEMCAD) and the simulated SAR distributions on the phantom head for the proposed antenna at the bottom position of the mobile phone. The SAR distributions in the figure are normalized; 0 dB indicates the maximum SAR value.

The SAR results are analyzed with the aid of the SAR simulation model provided by SEMCAD [29]. The simulation model is shown in Fig. 7, and the simulated normalized SAR distributions on the phantom head for the proposed antenna at the bottom position of the mobile phone are shown in the figure. Note that it has been shown that this kind of internal mobile phone antenna (no ground plane below or behind the antenna's radiating portion) is more suitable to be placed at the bottom position of the mobile phone to achieve decreased SAR values [1], [22]. In the simulation model, the system ground plane is spaced 5 mm from the phantom ear, and the mobile phone is oriented 60° to the vertical axis of the phantom head. The testing power is 24 dBm at 859 and 925 MHz, and 21 dBm at 1795, 1920 and 2045 MHz [1], [22]. From the results, the obtained SAR values for 1-g (10-g) head tissue are 1.25 (0.93), 1.08 (0.79), 0.68 (0.44), 0.60 (0.37) and 0.50 (0.31) W/kg at 859, 925, 1795, 1920, and 2045 MHz, respectively, which all meet the SAR limitation of 1.6 (2.0) W/kg [19]. Also note that there are two local SAR maxima observed at 1795, 1920 and 2045 MHz, which indicates that the antenna's near-field radiation energy is more uniformly distributed; this behavior results in decreased SAR values. The obtained SAR results for the proposed antenna are also about the same as those of the two-strip monopole antenna obtained in [1].

IV. Conclusion

A simple printed monopole using a chip inductor for achieving a frequency ratio of about 1 to 2 for its first two modes and moreover obtaining a small resonant length of about 0.17 wavelength for its first mode for WWAN operation in the mobile phone has been proposed. With a simple structure, the antenna requires a small printed area of about 250 mm^2 only. The antenna's first two modes can be controlled to occur at about 900 and 1900 MHz to cover GSM850/900 and GSM1800/1900/UMTS bands. Good radiation characteristics over the five operating bands have been observed. The SAR of the antenna mounted at the bottom position of the mobile phone has been conducted. The obtained SAR values meet the requirements for practical applications.

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